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Experimental and Theoretical Studies of Near-bottom Sediments to Determine Geoacoustic and Geotechnical Properties

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Abstract:

In a program designed to develop methods for predicting and measuring certain geoacoustic and geotechnical properties of the sediments immediately beneath the sea floor, several new tools were developed to measure *insitu* properties such as undrained shear strength, shear wave velocity and angle of internal friction. These tools include a motorized penetrometer designed to measure quasistatic cone penetration resistance up to depths of two meters into the bottom, a Love wave source and linear receiving array to measure shear wave velocity, and a 22-caliber source and array designed to generate Scholte waves with higher dominant frequency than conventional airgun sources. Using data obtained with this equipment as well as from other CBBL investigators, dynamic shear moduli derived from measurements of shear wave velocity were correlated with cone penetration resistance and the results were found to be consistent with results obtained by geotechnical engineers for many different clay soils. This result suggests that their regression equation may also be used for marine sediments of the type tested in the current program. In addition to the above work, the Biot-Stoll model was used to establish a baseline geoacoustic model for the soft, gassy soils of Eckernfoerde Bay which constitutes the starting point for studies of the perturbing effects of free gas bubbles and other scatterers in the sediment.

Objectives:

The main objective of our work in this program was to develop methods for predicting and measuring certain geoacoustic and geotechnical properties of the sediments immediately beneath the sea floor. In particular we focused on *insitu* shear strength and shear wave velocity and how they are related. The shear strength, which is a large-strain parameter usually expressed as undrained shear strength, s_u, in fine-grained sediments or angle of internal friction in coarser granular sediments, plays a fundamental role in determining the penetration and stability of mines deployed on the seafloor. On the other hand, the shear wave velocity is a small strain parameter which has been studied extensively in recent years because of its importance in the determination of bottom loss in long-range propagation in shallow water. It is also an important input parameter in all comprehensive seafloor geoacoustic models [Stoll, 1989].

A second objective of our work was to develop a baseline model for soft sediment that would match the response measured by various investigators in both the low and high frequency

ranges and thus would be a unified starting point for studies of the effects of free gas and other discontinuities.

Approach:

During the first two years of the CBBL program several new tools were developed to measured the properties mentioned above, These include a torsional wave source which generates Love waves in the sediment near the sea floor and a quasistatic cone penetrometer designed to measure shear strength . In addition, a p-sv wave source, which utilizes 22-caliber blank cartridges, was developed to generate low amplitude pulses with a somewhat higher dominant frequency than conventional airguns. These new tools are described in detail in [Stoll et al, 1994]. A photograph of the Love wave generator and the quasistatic cone penetrometer mounted on a self-righting sled is shown in Figs. 1.

In addition to the design and construction of new tools for *insitu* measurements, new computer programs for inverting the field data were developed. These include a program for analyzing the dispersion of Love waves generated by the torsional wave source mentioned above. This analysis determines velocity of horizontally polarized shear waves as a function of depth for the first several meters of sediment below the sea floor [Bautista and Stoll, 1995].

The equipment and techniques developed during the CBBL program were used in a number of field experiments:

1. Baltic Sea at Eckernfoerde , Germany in cooperation with FWG, May 1993.
2. Gulf of La Spezia, near SACLANT Undersea Research Center, La Spezia, Italy, May 1993.
3. Gulf of Mexico, near Panama City, Florida, August 1993.
4. Baltic Sea at Eckernfoerde, Germany in cooperation with FWG, June 1995.

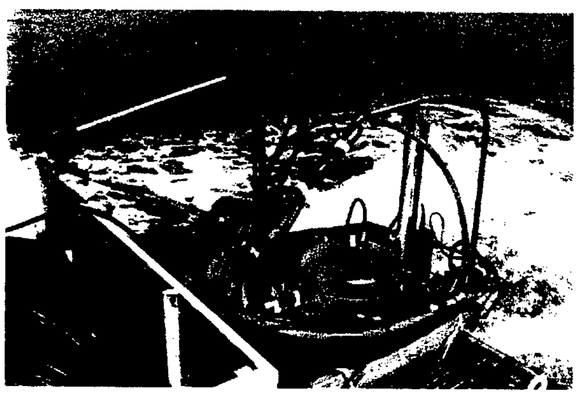

Fig. 1 Torsional source and cone penetrometer mounted on self-righting sled.

The 1993 work in Eckernfoerde and the Gulf of Mexico was supported by the CBBL program whereas the work in Italy and the 1995 work in Germany were supported by ONR (U.S. Liaison Officer to SACLANT Center) and SACLANT Center.

Results:

As mentioned above, several new field techniques were developed to study *insitu* properties of the sediment immediately below the bottom. Development and testing of much of the necessary equipment was carried out during the first two years of the CBBL program.

Unfortunately, cutbacks in funding during subsequent years did not permit utilization of the new equipment to the fullest extent since we were unable to participate in the Key West or California experiments. As a result only a limited amount of field data was obtained, mainly from the 1993 and 1995 work in Eckernfoerde and the experiments in the Gulf of Mexico. One of our main objectives was to see if *insitu* shear strength, or alternatively, quasistatic cone resistance, Q_c, could be correlated with dynamic shear modulus G_{max} or shear wave velocity. A plot of G_{max} versus Q_c is shown in Fig. 2. In this figure, some of the values of shear modulus are based on measurements by Richardson et al [personal communication] using the ISSAMS probes and some were made with our shear wave source. From this preliminary figure it appears that there is a definite correlation between these two dissimilar properties (i.e., one small strain anelastic and the other large strain, plastic) and we hope to expand our data base relating to these two parameters in the future.

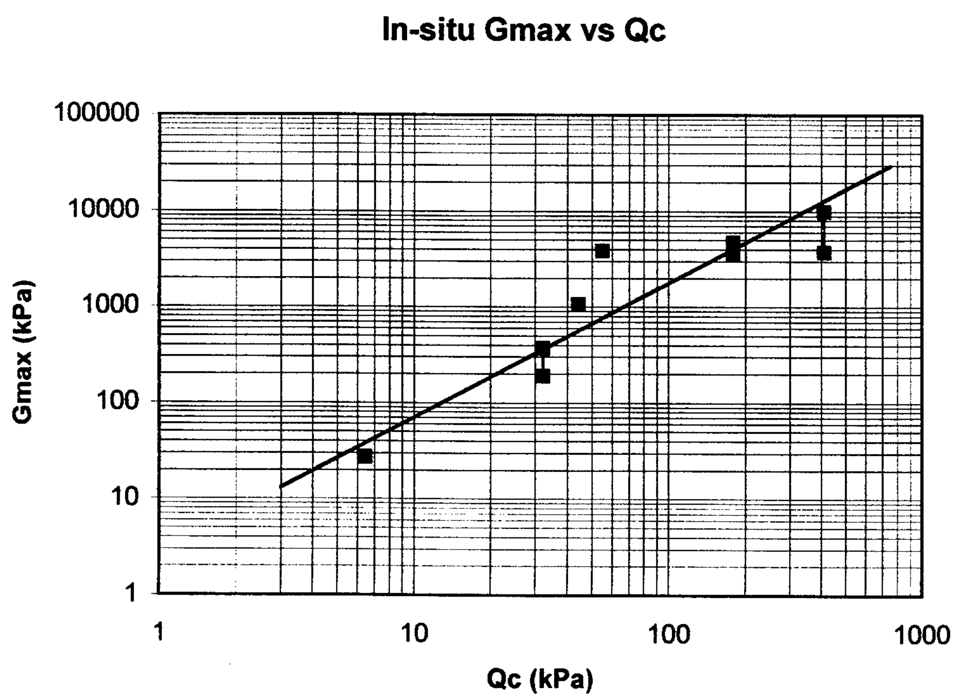

Fig. 2. Shear modulus calculated from shear wave velocity versus quasistatic cone penetration resistance. The solid line which has the equation $G_{max} = 2.87\ Q_c^{1.335}$ is based on a regression analysis of 481 tests on 31 clay soils located worldwide [Rix and Mayne, 1993]

One of the more important uses of the data collected during the CBBL program is the benchmarking or "ground truthing" of models that are used to predict velocity and attenuation in the near-bottom sediments. Measurements by various participants in the program resulted in some data taken at high frequencies using pulse propagation techniques whereas other data was obtained at low frequencies typical of interface wave experiments. Data from both kinds of measurement were used as input in constructing a "baseline" model using the Biot theory, which is valid over a wide frequency range [Stoll,1998] and serves as a starting point for studies of the effects of discontinuities in the structure of a sediment. In another paper [Stoll, 1997], an

operator proposed by Biot, that results in a response like that of a harmonic oscillator, was incorporated into the baseline model to show the effects of bubble resonance for the case where free gas exists as bubbles in the pore spaces.

Accomplishments:

The main accomplishments of our work include the development of new field methods to measure shear wave velocity and attenuation and to measure *insitu* shear strength. Since the shear wave measurements are made at low frequencies they provide information that cannot be obtained with pulse measurements using probes of the type used on the ISSAMS apparatus or the acoustic lance used by others in the CBBL program. Moreover by measuring both velocity and strength *insitu* on undisturbed sediment, we have been able to obtain a correlation that would be questionable if it had been done on laboratory specimens which are subject to sampling disturbance and changed environmental conditions.

Our application of the Biot model to the CBBL data for the soft sediments of Eckernfoerde Bay showed how the theory may be used to bridge the gap between high and low frequency data in building a unified baseline model. It also highlighted the the fact that more data on the low frequency dilatational response (velocity and attenuation) are needed to fully define the "best" model.

In addition to measuring shear strength for correlation with other sediment properties as described above, the cone penetrometer developed early in the CBBL program has been used to measure penetration resistance as a function of depth for a variety of different purposes ranging from the measurement of sand-cap thickness over dredge spoil areas to the establishment of "ground truth" in the development of a dynamic seafloor penetrometer. Improved versions of the penetrometer have been built as permanent equipment for the Naval Research Lab (for installation on their ISSAMS system) and for SACLANT Undersea Research Center.

Finally, an important spinoff of our CBBL work should be mentioned. Several versions of the quasistatic cone penetrometer developed in 1993 have been used to provide "ground truth" in the development of an expendable bottom penetrometer (XBP) that can be launched from a moving ship and is used to assess the penetration resistance of the seafloor to determine the potential for mine burial. The XBP is similar in shape and size to a standard bathythermograph (XBT) and uses the same double-spool, fine-wire system for data transmission. However in the XBP, the thermistor used to measure temperature in the XBT is replaced by an accelerometer which measures deceleration as the probe penetrates the seafloor. The record of deceleration is then inverted to obtain cone resistance or shear strength as a function of depth as well as information pertaining to the dynamic shear modulus of the sediment. To date over 500 XBPs have been deployed in areas where the sediment varied from soft mud to compact sand and a U.S. patent has been obtained for the system [Stoll and Akal, 1997]. Without the aid of the cone penetrometers developed under the CBBL program, it would have been impossible to evaluate the performance of these probes and to create a comprehensive data base relating probe signature to sediment properties.

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Funding received	156,000	94,000	15,500	27,553

Publications:

<u>Peer reviewed</u>

Stoll, R. D., Bautista, E. and Flood, R. (1994) "New tools for studying seafloor geotechnical and geoacoustic properties," J. Acoust. Soc. Am.,**96**, 2937-2944.

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<u>Symposium proceedings</u>

Stoll, R. D. and Bautista, E. O. (1995) "Measuring near-bottom shear wave velocity using Love waves," Proc. Workshop 'Modelling Methane,Rich Sediments of Eckernfoerde Bay', Eckernfoerde, Germany, 26-30 June, 1995.

<u>Dissertation</u>

Bautista, E. O. (1994) "Remote determination of *insitu* sediment properties using Love waves," Ph.D. dissertation, Columbia University.